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INDOOR PROPAGATION AND BIT ERROR RATE MEASUREMENTS AT 60GHz USING PHASE-LOCKED OSCILLATORS

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ABSTRACT

This paper describes the propagation and bit error rate measurements that have been conducted within buildings using phase-locked oscillators at 60GHz. The propagation measurements were conducted to study the envelope distribution, the power law with distance for different environments, the signal coverage, the received power spectrum, and edge diffraction effects. Measurements were also conducted to determine the BER performance in fading for FSK modulation at 240 and 480kbit/sec for both LOS and non-LOS conditions.

INTRODUCTION

The demand for mobile services has increased rapidly over the past 25 years or so with a growth rate of approximately 12% per annum. The common belief in Europe is that this rate will be maintained at least to the end of the century. To date, the solution to this shortage of available radio spectrum has been to use higher frequencies in the UHF band (i.e below 1GHz) and to reduce the channel spacing of existing modulation systems. Research is taking place to develop new spectrum efficient modulation techniques and systems. However, in order to meet this continuing demand and so avoid severe spectrum congestion in the future, there is a need to investigate the suitability of frequency bands above 1GHz for mobile radio.

A region of radio spectrum is therefore being sought which could accommodate large numbers of users and wideband services especially in the usual demand 'hot spots' such as city centres, office blocks, factories, etc. One such region is the millimetric waveband around 60GHz for providing integrated personal communications and a wide range of digital services to mobile users and data terminals. Futhermore, with recent advances in GaAs technology and signal processing, the use of 60GHz in broadband short-range point-to-point links is also the subject of much investigation at the moment. However, this frequency band is unsuitable for long range communications because of the 10 to 16 dB/km attenuation due to oxygen absorption. The work presented here is concerned with propagation and bit error rate measurements conducted within buldings using phase locked oscillators at 60GHz.

EQUIPMENT AND EXPERIMENTAL PROCEDURE.

The signal strength measurements were made with the experimental system shown in fig. 1. A 50mW, 59.9GHz phase-locked oscillator was used for the transmitter and a 10mW, 58.9 GHz phase-locked oscillator was used as the receiver local oscillator. In the receiver, a single balanced mixer was used to downconvert to a 1GHz IF. This IF was amplified and passed through a 1GHz bandpass filter for image rejection and then was further down converted to an IF of 60MHz. This IF was passed through a log amplfier, whose output was recorded on an FM tape recorder. An IBM model AT computer incorporating a 20 megabyte hard disk and A/D converter was used for digitising and analysing the recorded data.

Fig. 2 shows the experimental system used for the BER measurements. The FSK encoder had a centre frequency of 60MHz, and had a 127 bit length pseudo random binary sequence (PRBS) as its data input. A 60GHz modulator was used to upconvert to 60GHz. The output of the modulator consisted principally of 2 sidebands at 59.96GHz and 59.84GHz (60MHz above and below the 59.9GHz output from the phase-locked transmitter oscillator). Because it was too difficult to design a filter at 60GHz, both sidebands were transmitted. The loss of the modulator was 10 dB, so the transmitted power was 5mW. At the receiver, the 58.9GHz phase-locked local oscillator down-converted the transmitted sidebands to 1.06GHz and 0.94GHz. The bandpass filter passed only the 1.06GHz sideband, which was down-converted to 60MHz. A limiter, a frequency discriminator and an integrate and dump filter were used for the FSK demodulator. The output of demodulator was compared with the transmitted PRBS sequence, so that a pulse was produced for every error. These error pulses were counted with a frequency counter, and the errors produced were counted over a 10 seconds time period in order to determine the probability of error.

Two omnidirectional 60GHz aerials were used for the measurements which had gains of approximately 7 dB, elevation beamwidths of about 20^{o} and which were circularly polarised. These aerials were used for most of the propagation and BER measurements. For the edge diffraction measurements, a standard 20 dB gain horn aerial with a beamwidth of 18^{o} was used for the receiver, and a high directivity horn-lens aerial was used for the transmitter. The horn-lens aerial had a gain of 37 dB, a beamwidth of 2.4^{o}, and sidelobes whose amplitudes were more than 27 dB below the main lobe. This type of aerial

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was used because the measurements had to be free of any significant reflected components.

The measurements were conducted within the Queen's Building of the University of Bristol, a substantial three storey brick and reinforced concrete building. For the majority of the measurements, the transmitter and the receiver were positioned 1.5 m above the floor. For the envelope distribution measurements, the signal coverage measurements and the BER measurements in fading, the transmitter was scanned over a small area to collect the data as detailed in reference [1]. Within the scanned locations, the mean signal strength was approximately constant so that the mean or median signal power, or the envelope distribution could be accurately determined.

ENVELOPE DISTRIBUTION MEASUREMENTS

Line-of-sight (LOS) and non-LOS measurements were made with the receiver stationary and the transmitter randomly moved in a horizontal plane. Fig. 3 shows the received signal power against time when there was no LOS path between the transmitter and receiver. This illustrates the nature of the fast fading experienced within buildings. Fig. 4 shows the cumulative distribution function (CDF) of the received signal envelope for both LOS and non-LOS conditions and also the theoretical Rayleigh CDF. When there was a LOS path between the transmitter and receiver, the envelope distribution significantly departed from the Rayleigh distribution and tended to follow a Rician distribution. It is interesting to note that when there was no LOS path, the distribution was approximately Rayleigh. The LOS result was as expected, since the signal was received via many reflections off nearby objects such as walls, furniture, ceiling and floor, and with no direct component, the envelope distribution should follow the Rayleigh distribution [2]. When a LOS path does exist, the signal so received is likely to be much stronger than the signal received via the reflected paths, so the distribution should depart from the Rayleigh distribution and become a Rician distribution [3].

When both the transmitter and receiver are stationary, the signal reaching the receiver is randomly affected by people or objects moving in the area. The results have shown that when a LOS path existed, the envelope distribution when a person was moving behind and in front of the receiver at a distance of 0.25m did not obey the Rayleigh distribution. However, when there was no LOS path the envelope distribution exhibited a near Rayleigh distribution. Fig. 5 shows the received signal power against time when a LOS path existed and a person was moving in front of and behind the receiver.

MEDIAN RECEIVED SIGNAL POWER AGAINST DISTANCE DEPENDENCY MEASUREMENTS

These measurements were conducted under LOS conditions with the receiver stationary and the transmitter on a trolley pushed at a constant speed so that the time to distance conversion was linear. The received signal power was averaged over approximately 40 wavelengths. This distance was long enough to filter out most of the short term variations (fast fading), but short enough so that it did not significantly affect the variations in the median level [4]. In order to determine the propagation exponent, a straight line curve fit was performed on the median received signal power.

Different environments within buildings have different influences on the received signal power. Four areas have been examined: two types of corridor, a Laboratory, and an office. Details of these measurement areas and their influence on signal propagation are given below.

The first corridor was narrow with dimensions 18m x 1.8m x 2.7m (length x width x height) and had metal lockers along one side. The second corridor was wider with dimensions 18m x 3m x 2.5m (length x width x height) and had glass panelling on both sides. Both had 30cm thick plaster covered concrete walls and the floors were covered with varnished cork tiles. Fig. 6 shows the received signal power along a wide corridor. The median received signal power for the corridors decreased with distance as $1/d^{1.32}$ and $1/d^{1.20}$ respectively. The propagation laws for both corridors were therefore very similar, and the signal power fell more slowly than it would in free space. Theoretically, a $1/d^2$ law occurs in free-space, and this has been confirmed outdoors over short distances when reflections were minimised. The slow fall-off in signal power in the corridors was probably due to the smooth parallel walls, floor and ceiling which produced strong specular reflections which channelled the power to the receiver.

The laboratory was a 24m x 5.5m x 3.75m (length x width x height) room with 30cm thick plaster covered concrete walls and a floor covered with varnished cork tiles. There were many chairs and wooden benches in the room, and a large amount of electrical equipment. The median signal power decreased as $1/d^{1.71}$, which was a faster fall with distance compared to the corridors but was still slower than it would be in free-space. Presumably, the channelling effect was still present, but to a smaller degree because the benches and equipment prevented strong specular reflections off the walls, although there could still be strong reflections off the floor and ceiling.

The office was a postgraduate work room, which was 15.5m x 3.5m x 5m (length x width x height) with plaster covered concrete walls and a carpeted floor. There were many desks, chairs and bookshelves in this room. Fig. 7 shows the received signal power against distance within the office. The median signal power decreased as $1/d^{2.17}$, which was faster than the other areas tried and quite close to the $1/d^2$ free-space law. This was probably because the furniture and carpet prevented strong reflections off the walls and the floor. This was confirmed by the envelope fading which was less severe than in the two corridors and the laboratory. Fig. 8 shows the scatter plot of the median signal power against distance for the above environments.

SIGNAL COVERAGE MEASUREMENTS

Measurements have been conducted in an area with many offices separated by metal partitions. The transmitter was carried around the rooms and the signal was received at a fixed point in the middle of the room. The results have shown that, as expected, the 60 GHz signal is effectively screened by the metal partitions. However, when the transmitter and receiver were in the same room, a high signal power was maintained, although with severe multipath effects.

Measurements were also conducted within an area with corridors and rooms having concrete walls and wooden doors. The signal power when the transmitter and receiver were in different rooms was generally too small to be usable. There was, however, some leakage through the wooden doors, resulting in a high received signal power near them or when there was a LOS path through them, but it was insufficient to give adequate room to room coupling. This situation was illustrated by three median signal power measurements which were made at transmitter-receiver separation distances of about 11m. The first was a LOS measurement, the second was blocked by a 4cm thick wooden door made of oak, and the third was blocked by a 40cm thick plaster covered concrete wall. The losses relative to the LOS path were 7 dB for the path through the wooden door and 27 dB for the path through the concrete wall.

Median signal power measurements have been made with the receiver placed at ceiling height in the middle of a large room. The results have indicated that the signal power was at its lowest behind obstructions but was generally higher here compared to when the receiver was 1.5m above the floor. The signal could cover the whole room even though there was no LOS path between the transmitter and receiver at certain locations. It therefore seems that a suitable position for the radio ports is at ceiling height in the middle of the room.

RECEIVED POWER SPECTRUM MEASUREMENTS.

Measurements were also conducted to determine the spectrum of the received signal by down-converting the 1 GHz IF to an IF about 3kHz, and monitoring the spectrum on a digital spectrum analyser. This signal was centred on the analyser when there was no movement between the fixed transmitter and receiver. When the transmitter was moved away from the receiver at a constant speed of about 1 m/s with a LOS path between the transmitter and receiver, the IF shifted upwards by about 200 Hz, as shown in fig. 9. Theoretically, for a mobile moving at a speed of about 1 m/s and a carrier of 60 GHz, the maximum doppler shift, fd, is 200 Hz.

The broad peak shifted by 600Hz (+3fd) could have been due to the signal reflecting back to the transmitter, which then reflected it to the receiver. The broad spectrum between -fd and +fd can be attributed to many reflections arriving from different angles, and therefore having doppler shifts between -fd and +fd.

EDGE DIFFRACTION MEASUREMENTS

Knife edge diffraction measurements were made using an aluminium sheet as the knife edge. The experimental results were found to fit the theoretical curve [5] as shown in fig. 10.

The loss at a diffracted angle of 110 (v=3) was 22 dB above the free-space loss, which is not excessively large. In practice though, obstructions cannot be considered to be knife edges of this form, so diffraction measurements were attempted around a metal covered wall. It was found, however, that even for a small diffraction angle of 30, the received signal was dominated by reflected signals. It is therefore likely that the diffraction around most obstructions will be small, and that reflections must be relied upon. Diffraction measurements outdoors are covered in another publication.[6]

BIT ERROR RATE (BER) MEASUREMENTS.

BER measurements were conducted for FSK modulation at 240 kbits/sec and 480 kbits/sec in both LOS and non-LOS conditions while moving the transmitter randomly in a horizontal plane in order to produce fading. The received signal envelope was recorded and analysed to obtain the mean signal power and the envelope distribution. The output noise power density was measured and the normalised SNR was calculated as the ratio of the average signal power to the noise power in a bandwidth equal to the bit rate. The SNR was varied by reducing the transmitted power with a variable attenuator. The results are shown in figure 11, where the BER varies as a function of the average, normalised SNR.

It is interesting to note that for non-LOS conditions, where the envelope was found to obey the Rayleigh distribution, the experimental curve for the probability of error was very close to the theoretical curve. Under Rayleigh fading conditions, in order to maintain an error rate of 1 in 10^3, an increase of 18 dB in the SNR was required compared with the required SNR in the absence of fading. However, when there was a LOS path between the transmitter and receiver, an error rate of 1 in 10^3 required an increase of about 13 dB in average SNR compared to that in the absence of fading.

Fig. 11 also shows that for the conditions of the experiments conducted in our laboratory, no irreducible error rate occurred for either bit rate under LOS and non-LOS propagation. This implies that the time delay spread was much less than the bit duration of the transmitted data and also that the random FM due to doppler shifts was much smaller than the FM of the FSK signal.

DISCUSSION AND CONCLUSIONS

This paper has presented the measured data for indoor 60GHz propagation characteristics and FSK BER measurements.

Generally, the non-LOS case causes the greatest difficulties since the median received signal power is at its lowest, the fast fading is more severe (Rayleigh) compared to that for LOS conditions (Rician), and the BER is at its highest. Attaching the radio transmitter near the middle of the ceiling can be expected to improve the signal strength behind obstructions. An aerial which directs the radiation downwards and sideways would probably improve the signal strength even further.

The screening effect of concrete walls means that one radio transmitter would be required per room. The low attenuation of wooden doors suggests that if the walls are made of chipboard, the signal would perhaps cover several rooms.

Doppler spreading is small indoors compared to the transmitted signal bandwidth of FSK, so its effects are likely to be small. This is confirmed by lack of an irreducible error rate with the BER measurements. The results have also indicated that a relatively low attenuation of signal strength occurs with knife edge diffraction. However, practically occurring diffractors (obstacles) do not have knife edges, and the received signal power due to diffraction is generally small compared to that due to reflections.

Since no irreducible error rate occurred in the BER measurements at 480 kbits/sec, it is possible that a higher bit rate could be used without problems of intersymbol interference caused by time delay spread. However, in other areas, the time delay spread may be higher, so a lower bit rate would have to be used.

The results have indicated that 60GHz could be used for wideband integrated portable communication systems within buildings. A single room or corridor could be served by a single 60GHz distribution point attached to the ceiling. Each room or corridor would then be a microcell. Optical fibre links could be connected to the 60GHz distribution points for trunking purposes.

Acknowledgement

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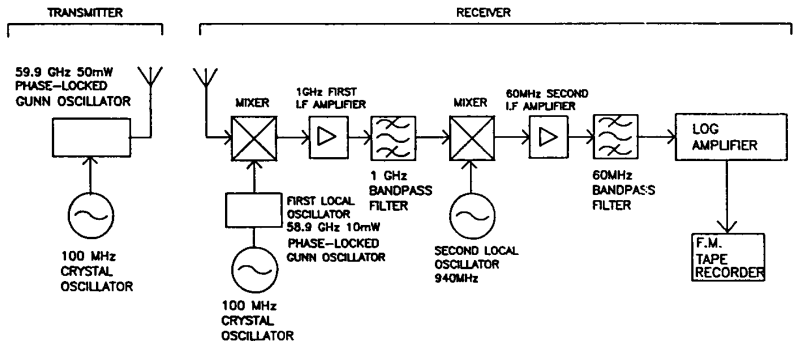

FIG. 1 EQUIPMENT FOR THE PROPAGATION MEASUREMENTS.

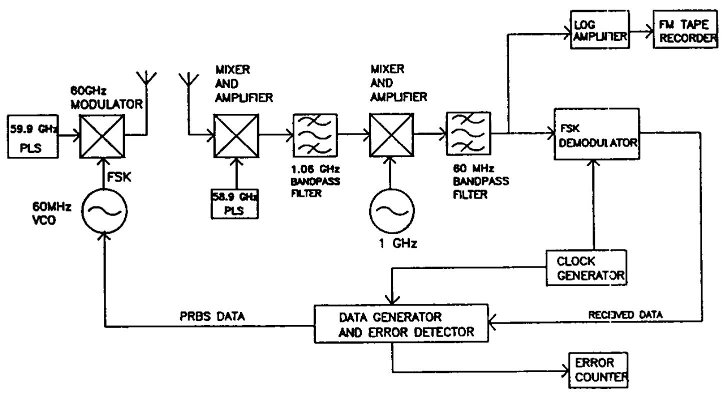

FIG. 2 EQUIPMENT FOR BER MEASUREMENTS.

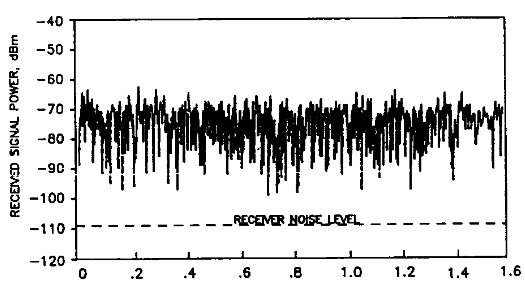

FIG. 3 RECEIVED SIGNAL POWER WHEN THERE WAS NO LOS PATH BETWEEN TRANSMITTER AND RECEIVER FOR RANDOM SCANNING OF THE TRANSMITTER AT ABOUT 0.8m/sec.

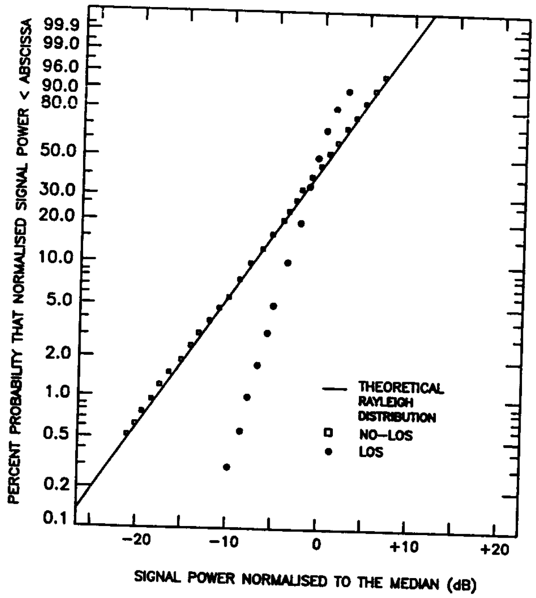

FIG. 4 CDF OF THE RECEIVED SIGNAL POWER FOR LOS AND NON-LOS CONDITIONS WITH THE TRANSMITTER MOVING.

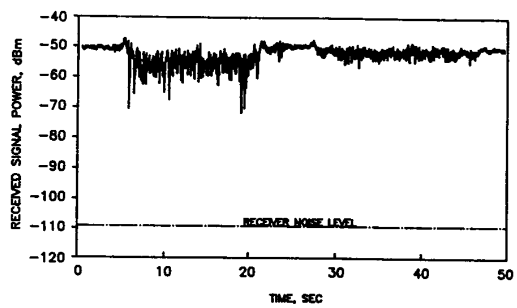

FIG. 5 RECEIVED SIGNAL POWER WITH THE TRANSMITTER AND RECEIVER FIXED AND A PERSON MOVING IN FRONT OF AND BEHIND THE RECEIVER (LOS)

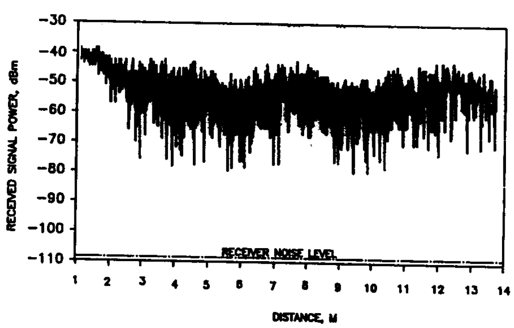

FIG. 6 RECEIVED SIGNAL POWER ALONG A WIDE CORRIDOR.

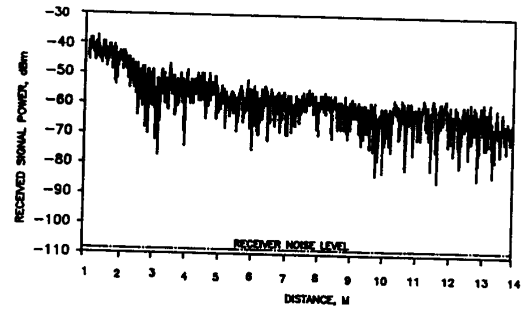

FIG. 7 RECEIVED SIGNAL POWER WITHIN AN OFFICE.

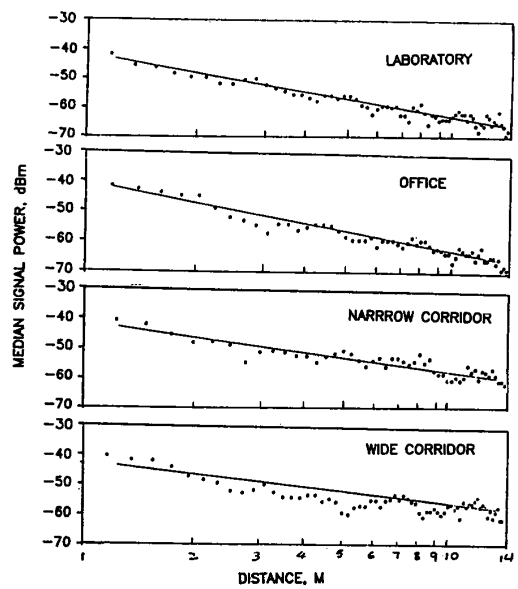

FIG. 8 SCATTER PLOT OF THE MEDIAN SIGNAL POWER AGAINST DISTANCE (LOG SCALE)

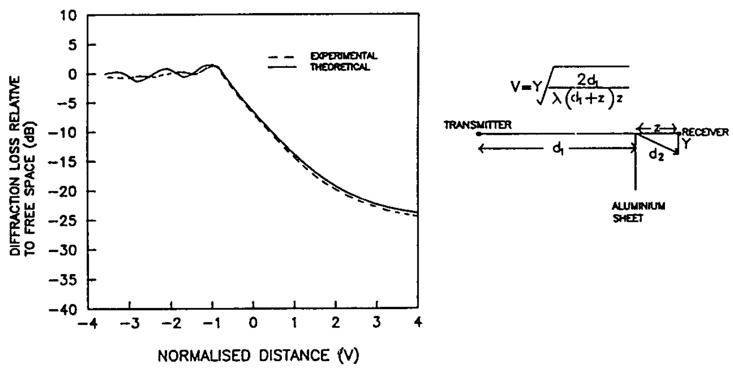

FIG. 10 KNIFE EDGE DIFFRACTION LOSS MEASUREMENTS.

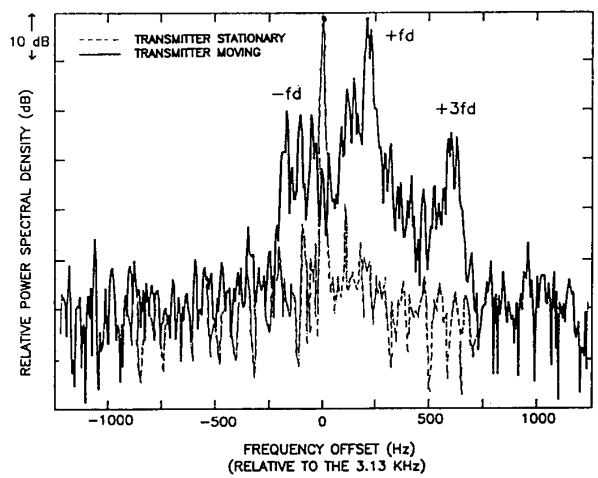

FIG. 9 POWER SPECTRUM OF RECEIVED SIGNAL

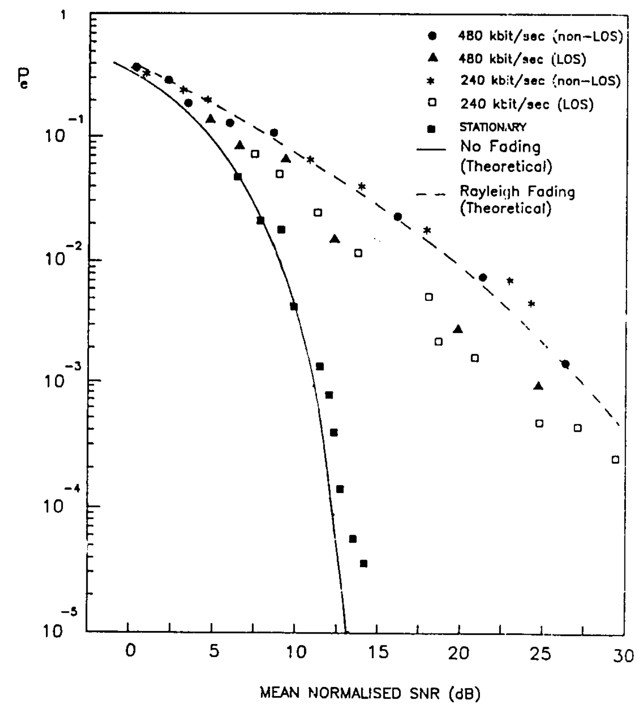

FIG. 11 BER IN FADING AND NON−FADING CONDITIONS FOR NON−COHERENT FSK.